Experimental demonstration of bidirectional light transfer in adiabatic waveguide structures

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We propose and demonstrate a novel type of optical integrated structure consisting of three adiabatically coupled waveguides arranged in an N-shaped geometry. Unlike conventional adiabatic three-waveguide couplers mimicking the stimulated Raman adiabatic passage (STIRAP) process which utilize solely the counter-intuitive coupling and thus operate only in one direction, our structure achieves complete bidirectional light transfer between two waveguides through the counter-intuitive and intuitive coupling in either direction, over a wide wavelength range. Moreover, the light transfer through the intuitive coupling is more efficient and robust than through the counter-intuitive coupling.

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The analogy between quantum systems and optical waveguide structures make the latter not only a favorable tool for emulating quantum phenomena, but also a powerful platform for the development of novel photonic devices [1-3]. One of such quantum-inspired photonic devices is the adiabatic three-waveguide coupler, which is reminiscent of the celebrated Stimulated Raman Adiabatic Passage (STIRAP) technique [4]. This adiabatic process is inherently tolerant to variations of the structure parameters and exhibits a broadband operation [5]. Owing to these advantages, the spatial analog of STIRAP has been employed to achieve robust and multi-wavelength light transfer [6-8], achromatic beam splitting [9,10], multi-wavelength spectral filtering [11,12], and two-photon quantum gate operations [13].

The success of STIRAP technique relies on the adiabatic evolution of a specific dark state of the involved three-level atomic system. To exploit this dark state, the acting laser pulses are arranged in a "counter-intuitive" sequence (the Stokes pulse ahead of the pump pulse). In such a counter-intuitive scheme, the population of atoms is adiabatically transferred from the initial state to the final state via the assistance of an intermediate auxiliary state which is not populated during the entire adiabatic passage [14]. The STIRAP in optical waveguide structures is implemented by appropriate engineering of the coupling strength between adjacent waveguides along propagation. Similar to the three-level atomic system, in adiabatic three-waveguide couplers, light can be completely transferred from one to the other outer waveguide via counter-intuitive coupling [15-19].

Besides the dark state, the bright state of a three-level atomic system can also be used for adiabatic population transfer. Such adiabatic passage scheme enabled by a pulse sequence acting in the intuitive order is termed 'bright-state STIRAP' or 'b-STIRAP' [20-22]. The b-STIRAP scheme was demonstrated experimentally in solid-state systems [20,21] and then studied theoretically in other systems under different settings [22-26]. In optics, while the basic STIRAP based on counter-intuitive coupling is well explored [17,18], there is no experimental demonstration of such intuitive-coupling-based b-STIRAP scheme, which will allow for bidirectional light transport in adiabatic waveguide structures.

In this Letter, we implement the intuitive coupling scheme in optical waveguides and demonstrate experimentally bidirectional adiabatic light transfer by employing an N-shaped waveguide structure with three supermodes. One of the supermodes is equivalent to a dark state of the adiabatic system, while the other two supermodes correspond to bright states. Either the dark state or one of the bright states can be used as a channel for adiabatic passage. Therefore, one can employ the counter-intuitive and intuitive coupling schemes to achieve adiabatic light transfer in two opposite directions, respectively. Importantly, the schemes containing three waveguides are theoretically more robust and allow flexible mode shaping compared to two-waveguide schemes with adiabatic coupling [26].

The schematic diagrams of the N-type adiabatic waveguide coupler and its working principle are shown in Fig. 1. The structure is a variant of the conventional STIRAP waveguide design [15-19]. Specifically, we consider a coupler composed of Ti-diffused waveguides permeating and merging with each other to form an N shape. We implement such an adiabatic coupler with titanium in-diffused waveguides in a lithium niobate substrate. Fig. 1(a) depicts a typical refractive index distribution of the designed N-type coupler. Two parallel straight waveguides are merged with an inclined waveguide at the opposite ends. The whole structure is slowly varying along the z direction. At z = 0, the structure can be described as a single-mode waveguide and a bimodal waveguide weakly coupled to each other. The three local supermodes at z=0 are also illustrated in Fig. 1(a). It can be seen that the first two supermodes match isolated waveguide modes well. As will be explained below, the two supermodes are equivalent to a bright state and a dark state, respectively, which offer two different adiabatic coupling schemes.

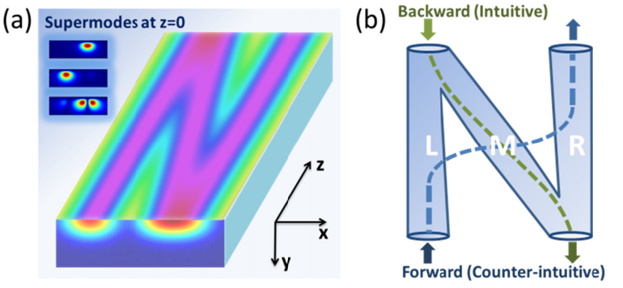

Fig. 1. (a) Schematic of the N-type adiabatic waveguide coupler. The images in *xy* and *xz* planes show the refractive index profiles at $z = 0$ and $y = 0$, respectively. The three supermodes of the structure at z=0 are also depicted. (b) Principle of bidirectional light transfer. Forward and backward complete light transfer are implemented through two different (counter-intuitive and intuitive, respectively) adiabatic processes. The waveguides from the left to the right are labelled as L, M, and R, respectively.

Adiabatic light transfer between waveguides is based on the evolution of a single supermode of the structure. As shown in Fig. 1(b), in the forward propagation case, the coupling is counter-intuitive and the incident light entering the left waveguide (L) is initially coupled into the 1st order supermode. As the supermodes are mutually orthogonal, the light will always reside in the 1st order supermode, provided that the structure is altered slowly enough, i.e. adiabatically. As a consequence, the light will be completely transferred to the other waveguide (R) due to the central symmetry of the structure as a whole. Note that during the entire propagation there is no light coupled to the middle waveguide, which is the reason why we claim such a supermode is equivalent to the dark state in atomic systems. In the backward propagation case, the light originally coupled into the 0th order supermode can be completely transferred to the other waveguide via intuitive coupling. This provides an intuitive STIRAP scheme in addition to the counter-intuitive STIRAP scheme, thus enabling complete adiabatic transfer of light in both the forward and backward directions.

In order to test our idea experimentally we have designed a waveguide coupler operating at the telecomm band around 1.5 μm. The coupler is fabricated by titanium in-diffusion in an x-cut $LiNbO_3$ wafer. The incident light is assumed to be TM polarized to experience the ordinary refractive index. The widths of waveguides are tapered, as schematically shown in Fig. 2(a), to compensate for the Ti sideway diffusion of converging waveguides. The tapering weakens an unwanted increase of the effective refractive indices between the converging waveguides [see Fig. 2(b)], which reduces unwanted coupling effects, thus allowing efficient adiabatic light transfer. The layout is displayed in Fig. 2(a) and the geometric parameters are: $L = 5$ cm, $w_1 = 5.4$ μm, $w_2 = 4.6$ μm, $w_3 = 5.0$ μm, $s_1 = 6.5$ μm and $s_2 = 21.5$ μm. The length is sufficiently large to ensure the fulfillment of the adiabatic criteria [26]. The values of s_1 and s_2 are carefully chosen to meet the requirement $k_{12} \ll k_{23}$ at $z = 0$, where k_{12} is the coupling coefficient between waveguides L and M, and k_{23} is the coupling coefficient between waveguides M and R. More specifically, for our fabricated structure $k_{12} / k_{23} \approx 0.01$ at $z = 0$. Fig. 2(b) shows the refractive index profile of the coupler at $z = 0$. The middle and right waveguides (M and R) merge into a bimodal waveguide due to the nature of fabrication based on titanium indiffusion. With the above designed geometrical parameters, the fundamental mode of this bimodal waveguide is tailored to be nearly identical to the mode of the left waveguide (L).

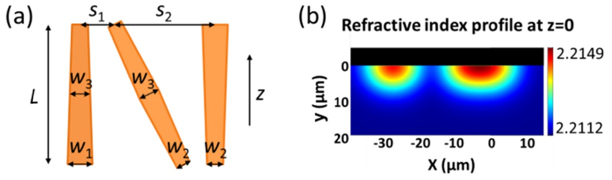

Fig. 2. (a) Layout of the mask defining the structural geometry of a three-waveguide coupler composed of three tapered Ti-diffused waveguides. L is the coupler length along z direction. s_1 and s_2 are the separations between the middle waveguide and the corresponding outer waveguides, respectively. $w_{1,2,3}$ are the widths of waveguides at various z-positions. (b) Color plot of the refractive index profile at the start of the coupler ($z = 0$).

Next we numerically calculate the supermode profiles and simulate the light propagation in our structure at the designed wavelength of 1550 nm. The evolution of the modal field profiles is shown in Figs. 3 and 4. The simulation results are obtained using a BPM method (Rsoft BeamPROP). Figure 3(a) illustrates the calculated supermodes at different positions along the coupler and the corresponding effective refractive indices. The 1st order supermode corresponds to the dark state, as there is a very weak excitation of the central waveguide at all z. The 0th and 2nd order supermodes are two bright states, with strong excitation of the central waveguide at $z \approx L/2$. We employ the 0th and 1st order supermodes as the two channels of adiabatic light transfer. Both the shape and the size of the two supermodes are tailored to be nearly identical at the start ($z = 0$) and at the end of the coupler ($z = L$). It can be noticed that the 1st order supermode does not exactly match the fundamental mode of the left waveguide. This imperfection is caused by the fact that at the input k_{12} / k_{23} is not zero. Although the ratio can be reduced by increasing the separation (s_2), a greater coupler length would then be required to meet the adiabatic criteria. However, the 0th order supermode matches the isolated waveguide mode perfectly well even if the separation is small, which leads to a better performance in adiabatic light transfer.

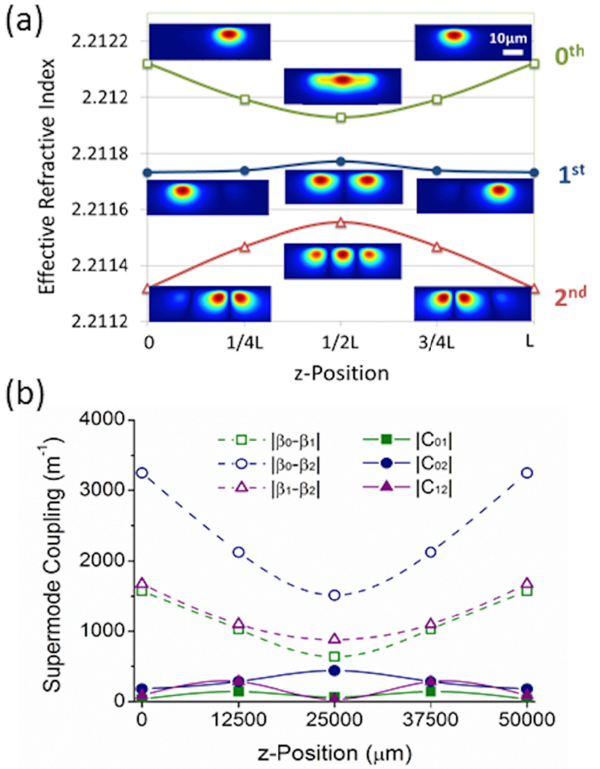

Fig. 3. (a) The effective refractive indices of three local supermodes of the N-type waveguide coupler at different positions along the propagation axis. The insets depict the corresponding modal intensity profiles ($|E|^2$) at the start, middle and end of the coupler. (b) Supermode coupling coefficients $|C_{jk}|$ at different waveguide cross-sections z (solid symbols and lines). The corresponding values of $|\beta_j - \beta_k|$ are also shown for comparison (open symbols and dashed lines).

To verify whether the structure is in the adiabatic regime, we employ the coupled supermode theory [28] for the dynamics of the supermode amplitudes b_j

$$\frac{\mathrm{d}b_j}{\mathrm{d}z} - i\beta_j b_j = \sum_k C_{jk} b_k, \tag{1}$$

where the supermode coupling coefficients are found as

$$C_{jk} = \left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \frac{k_0}{4} \frac{1}{\beta_j - \beta_k} \int_{A_z} \mathrm{e}_j^* \cdot \mathrm{e}_k \frac{\partial n^2}{\partial z} dA, \tag{2}$$

where j,k = {0,1,2} and j ≠ k; ε_0 is the vacuum permittivity, μ_0 is the vacuum permeability, $k_0 = 2\pi/\lambda$ is the wavenumber in free space, β_j and β_k are the supermode propagation constants, e_j and e_k are the electric fields of orthonormalized supermodes (we consider these modes to be pure TM modes with negligible electric field component along propagation), $n \equiv n(x,y,z)$ is the refractive index distribution, and the integration is performed over the whole transverse cross section $A_z(x,y)$. In this formulation, the adiabatic condition is $|C_{jk}| \ll |\beta_j - \beta_k|$. The dependencies of three supermode coupling coefficients along z are plotted in Fig. 3(b). It can be seen that the adiabatic condition is satisfied quite well, since the coupling coefficients C_{jk} are about one order of magnitude smaller than the corresponding values of $|\beta_j - \beta_k|$. It means that energy exchange between different supermodes is negligible along the propagation.

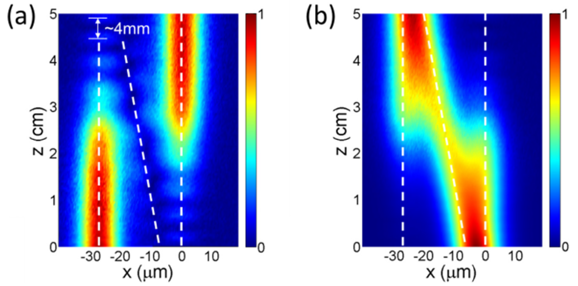

Fig. 4. Simulated light propagation showing |E| evolution in the counter-intuitive (a) and intuitive (b) coupling schemes. The white dashed lines indicate the symmetric axes of three waveguides.

Figure 4 presents the simulated light propagation in the N-type adiabatic coupler. We input the light from z=0 for both cases. The counter-intuitive coupling scheme corresponds to the forward propagation, while the intuitive coupling scheme is equivalent to the backward propagation owing to the structure symmetry [see Fig. 1(b)]. Nearly complete adiabatic transfer in both the counter-intuitive and intuitive coupling schemes is successfully achieved, which will allow for both the forward and backward cross coupling. We define the efficiency of bidirectional adiabatic light transfer by the coupling ratio parameter: $\mathrm{CR} = [P_R/(P_L+P_M+P_R)]_{z=L}$ for the counter-intuitive case, and $\mathrm{CR} = [(P_L+P_M)/(P_L+P_M+P_R)]_{z=L}$ for the intuitive case, where $P_{L,M,R}$ denote the modal power at the output of the corresponding waveguides, respectively. In the counter-intuitive case, we notice some mode beating patterns which indicate that the directional coupling also plays a role and ultimately limits the coupling ratio (CR≈0. 98). The beating length (~4 mm) agrees well with the value calculated from the effective index difference between different supermodes. In contrast, in the intuitive case, the mode beating effect is significantly suppressed and only a very small portion (<0.2%) of light has not been effectively transferred.

The fabricated sample is next characterized by excitation with a tunable diode laser (TDL) in the telecommunication wavelength range (S+C band). Linearly polarized light is coupled into either the left waveguide (L) or the bimodal waveguide (M+R) via a 10 × microscope objective and the output mode profiles are captured with a CCD camera. The measurements are carried out in the wavelength range of 1460 to 1560 nm, for both the counter-intuitive and intuitive cases, as shown in Fig. 5. In the counter-intuitive case, for wavelengths in the range of 1470 to 1550 nm over 0.960 coupling ratio is attained and the coupling ratio reaches a maximum of 0.980 at 1510 nm. After adopting the definition Crosstalk = 10 $\log_{10}$ (CR), we find that the crosstalk is lower than -15 dB for the range of 1480-1550 nm and at -10 dB level an over 100 nm bandwidth is obtained. However, there is an obvious drop in coupling efficiency when the wavelength is beyond this bandwidth. In fact, the coupling ratio at 1460 nm and 1560 nm are 0.915 and 0.949, respectively, which are quite low in comparison with the maximum value of 0.980. In the intuitive case, however, the coupling ratios are always relatively high (0.985-0.997) and the crosstalk is below -18 dB for all the wavelengths we have tested. This somewhat unexpected result suggests that the intuitive coupling scheme based on the adiabatic bright state could be a better choice for design of efficient and robust waveguide devices under specific conditions. Furthermore, the measured output mode profiles also confirm the high coupling efficiency of adiabatic processes, as shown in Fig. 5. It is evident that the light is cross-coupled from one to the other waveguide with negligible residual light in the original waveguide.

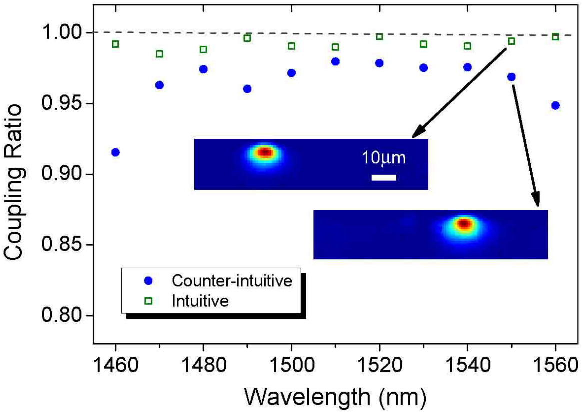

Fig. 5. Measured coupling ratio of the N-type waveguide coupler versus the wavelength of light, in the counter-intuitive and intuitive coupling schemes. The insets represent the corresponding output mode profiles at the wavelength of 1550 nm in the counter-intuitive and intuitive cases as indicated.

In conclusion, we have proposed and demonstrated experimentally an N-type adiabatic waveguide coupler that employs the evolution of both the dark and bright states in adiabatic transfer of light. This is an extension of conventional counter-intuitive STIRAP process to bidirectional adiabatic passage in optical waveguide structures. We also show that, compared to the counter-intuitive coupling, the intuitive coupling via the bright state is more efficient and more robust against the variation of the operating wavelength in our structure. The results presented here reveal the potential of adiabatic bright states in design of novel photonic devices and may stimulate further research and practical applications in integrated circuitry for classical [29,30] and quantum [31,32] optics. Other fields such as adiabatic frequency conversion [33] could also benefit from the application of bright state based schemes.

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